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The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards--the second order and residual first-order Doppler shifts. To this end ~~we study~~ suitable frequency reference transitions, ~~in~~ ions which are stored on electromagnetic traps and cooled by radiation pressure to less than 1K.

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Summary of Work on

"COOLED ION FREQUENCY STANDARD"

(FY 90)

submitted to

Office of Naval Research

ONR Contract No. N00014-90-F-0004

Project Leader:

D.J. Wineland

Frequency & Time Standards Group

Division 576

National Institute of Standards and Technology

Boulder, Colorado 80303

FTS: 320-5286

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Contract Description

The purpose of this work is to develop techniques to overcome the fundamental limits of present methods for high resolution spectroscopy and frequency standards--the second order and residual first-order Doppler shifts. To this end, we study suitable frequency reference transitions in ions which are stored in electromagnetic traps and cooled by radiation pressure to < 1K.

Scientific Problem

The scientific problems are (1) to find ways to suppress second order and residual first order Doppler shifts in atomic spectroscopy in a fundamental way--by substantially reducing the kinetic energy of ions stored ion electro-magnetic traps, (2) to study suitable reference transitions in ions that can be used as frequency standards, and (3) to study the problems (i.e., systematic effects) generic to all stored ion frequency standards. The goal is to achieve at least a factor of 100 improvement in accuracy over the present best device, the Cesium beam frequency standard, which has an accuracy of approximately 2 parts in 10^{14}.

Scientific and Technical Approach

Laser cooling is employed on all experiments in order to suppress Doppler shifts. Temperatures as low as 40 μK have been achieved and temperatures less than 0.1K are routinely achieved. To avoid light shifts on "clock" transitions we investigate "sympathetic cooling" where one ion species is laser cooled and by Coulomb collisions cools another ion species of spectroscopic interest. We continue experiments on Mg^+ and Be^+ in order to study generic problems with traps since these ions are easier to laser cool. We are conducting separate experiments for Hg^+ ions. These experiments have the goal of realizing a frequency standard with 10^{-15} or better accuracy.

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Summary of progress since Oct. '89. (details start on p.4)

(1) $^9Be^+$ frequency standard. We are currently trying to characterize an apparent pressure shift of the hyperfine clock transition which is much larger that expected. Elimination of this shift would make the Be^+ clock the most accurate atomic clock. Study of this shift is important because it may affect all high resolution measurements of hyperfine structure in atomic ions and possibly all clocks based on atomic ion hyperfine structure.

(2) Hg^+ optical frequency standard: Efforts this last year have concentrated on achieving extreme mechanical isolation for the cavity to which the laser local oscillator is locked. Beating together two lasers locked to independent cavities indicates the laser linewidth is less than 25 Hz which is the narrowest visible laser linewidth ever. Experiments to apply this new laser source to the ion are currently underway.

(3) Quantum Zeno Effect: The quantum Zeno effect is the inhibition of transitions by frequent measurements. Our published paper on this effect has generated rather widespread interest.

(4) Synchrotron Frequency Divider: Single electrons have been isolated. Parametric division (by 2) of the cyclotron resonance of electrons in a Penning trap has been observed.

(5) Linear Trap and High Resolution Microwave Spectroscopy of Hg^+ : An rf trap with linear geometry has been constructed. This trap should give, for many stored ions, the same small Doppler shifts as achieved for single ions in an rf trap of more conventional quadrupole geometry. Signal-to-noise ratio should be increased due to the larger numbers of ions.

(6) Laser Cooled Refrigerator and Detector: We have theoretically examined the possibility of extending laser cooling to cool and detect ions in a trap which is electronically coupled to a trap containing laser cooled ions. A trap along these lines is now being constructed. Such an experiment may have important implications for precise mass spectroscopy, magnetic moment ratio measurements, and other internal state spectroscopy.

(7) Penning Trap Density Limitations: We have identified a mechanism which limits the density which can be achieved in practice for ions in a Penning trap. This limit is caused by a static-field-axial-asymmetry-induced plasma heating resonance which depends on density and trapping parameters. Study of this effect has implications for all experiments on ions in Penning traps because it places a practical upper limit on the densities which can be achieved.

(1) Be^+ Frequency Standard

In this experiment, an oscillator has been locked to the (m_I = -1/2, m_J = 1/2) $\leftrightarrow$ (-3/2, 1/2) nuclear spin flip hyperfine "clock" transition ($\omega_0/2\pi \simeq 303$ MHz) in the ground state of $^9Be^+$. (Fig. 1)

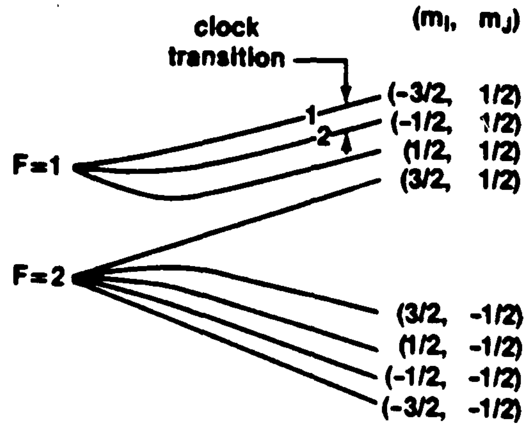

Fig. 1. Hyperfine energy levels (not drawn to scale) of the $^9Be^+$ 2s $^2S_{\frac{1}{2}}$ ground state as a function of magnetic field. At B = 0.8194 T the 303 MHz clock transition is independent of magnetic field to first order.

The basic idea of this experiment has been described previously. An apparent pressure shift of the clock transition frequency with an unexpectedly large value was discovered when the background gas pressure was increased. The background gas pressure could be increased by moving the magnet of the sputter ion pump which evacuated the trap region so that it overlapped fewer pumping cells and reduced the pumping speed. (We checked to make sure the magnetic field at the site of the ions was not disturbed.) The composition of the gas was not known since the pressure was measured with a Bayard-Alpert gauge. However, when the vacuum vessel containing the trap was initially evacuated the dominant background gases were H_2 and He as determined by a quadrupole mass analyzer. Therefore we expect that the background gas during the frequency standard measurements was either H_2 or He, or both. If the background gas was dominated by He, the fractional pressure shift was measured to be about $-3\times10^{-6}Pa^{-1}$; if the background was dominated by H_2, the pressure shift was measured to be about $-9\times10^{-6}Pa^{-1}$. Atomic ion hyperfine pressure shifts have previously been measured in $^{137}Ba^+$ (J. Vetter, et al., Z. Phys. A273, 129 (1975)) and in $^{199}Hg^+$ (L. S. Cutler, et al., Proc. 41st Ann. Symp. Freq. Control, 1983, p. 12) to be $5\times10^{-11}Pa^{-1}$ and $4\times10^{-11}Pa^{-1}$ respectively. The authors of the Ba^+ work show that the charge induced multipole interaction between the Ba^+ and the noble gas atoms used in that study should give an important contribution to the pressure shift. Since this interaction depends primarily on the polarizability of the neutral we would expect that the pressure shift for He atoms on $^9Be^+$ ions would not be significantly different than that for Ba^+ or Hg^+. Similarly, since the polarizability of H_2 is midway between Ar and Ne, we might expect the pressure shift for H_2 on Be^+ to be near those for Ne and Ar on Ba^+, which were measured to be $-6\times10^{-10}Pa^{-1}$ and $-6\times10^{-9}Pa^{-1}$ respectively.

The apparent large discrepancy between our data and other measured pressure shifts is not understood at this time, however, we are currently conducting studies to understand the effect. It should be noted that if the shift is real it may affect all rf and microwave frequency standards based on stored ions in a similar way. If so, it may be necessary to achieve significantly better vacuums by using liquid helium cryopumping. Nevertheless, once eliminated, it appears that the accuracy of ion frequency standards will be significantly better than the best reported Cs clock (1.5 parts in 10^{14}).

(2) Hg^+ Optical Frequency Standard

The basic idea for this experiment, which is illustrated in Fig. 2, has been discussed in previous publications. The goal of the experiment is to lock a laser "local oscillator" to the quadrupole transition in Hg^+. To obtain the best performance of the resulting optical frequency standard, it will be necessary to observe the linewidth of the quadrupole transition with a resolution of 2 Hz. The main problem in our experiment, as well as all other optical frequency standard experiments, is to have the laser spectral purity be narrower than the resonance line over the time it takes to lock the laser to the resonance line. The basic technique used to overcome this problem is to lock a laser to a stable reference cavity. In our experiment (and in other laser experiments reported), the laser tracks the cavity to much better than 1 Hz precision, but the cavity frequency is modulated by mechanical noise which changes the effective length of the cavity. We would like the laser linewidth to be less than about 2 Hz; at present it is around 25 Hz wide as determined by comparing this laser to another laser locked to a separate cavity (This measurement does not guard against common mode noise on the two separate cavities, but we took measures to make the two systems as independent as possible). Even though the laser linewidth is not less than two Hertz yet, the laser in our experiment has the best spectral purity of any laser ever reported.

The main effort this last contract period has been devoted to obtain a better "optical table" on which to mount the reference cavity to which the laser is locked. The problem with most conventional optical tables is that their cutoff frequency is too high, typically above a few Hz. By suspending a small optical table on "rubber bands" made of surgical tubing, we have achieved a natural resonance of the table below 0.3 Hz. We can get some idea of the performance of this system by comparing a laser locked to this cavity to a laser locked to a separate cavity on a second table. The second table is not as stable as the first, but preliminary observations indicate that the rubber-band table is significantly better than the previous optical table for this cavity. The real test is to now compare to the ion clock resonance line. These measurements are currently being attempted but results at present, are still to be obtained. One problem at the moment is that the reference cavity and ion trap are on separate tables. We have to correct for Doppler shifts between the tables due to velocities of 0.3 μm/s in order not to be sensitive at the one Hz level! Fortunately, we are able to use a Doppler cancellation scheme first used on Doppler ranging of rockets (see Vessot, et al., Phys.

Rev. Lett. 45, 2081 (1980).) In future versions we will mount the trap and reference cavity on the same table. Also in future experiments we hope to increase signal-to-noise by using the linear trap discussed below in part (5). This would reduce the servo attack time and reduce the importance of low frequency mechanical noise on the reference cavity.

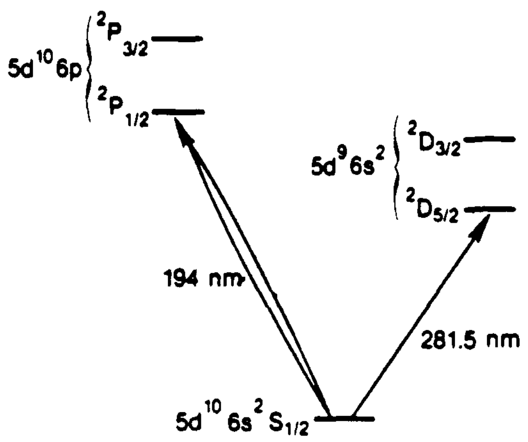

Fig. 2. Simplified optical energy-level diagram for Hg^+. The lifetime of the $^2D_{5/2}$ transition is about 0.1 s which would give a linewidth of 2 Hz on the electric quadrupole 281.5 nm transition. By observing the presence of or lack of fluorescence from the 194 nm transition, the quadrupole "clock" transition can be detected with 100% efficiency.

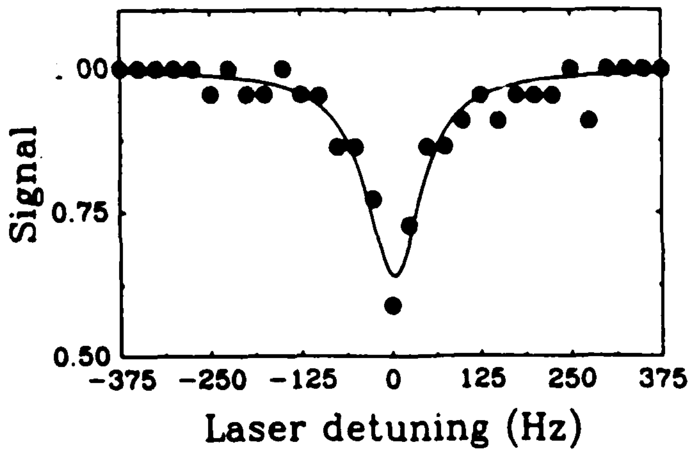

Fig. 3. The quantized fluorescence signal obtained from an 750 Hz scan of the 282 nm laser through the $^2S_{\frac{1}{2}}$(F = 0, m_F = 0) → $^2D_{5/2}$(F = 0, m_F = 0) component of the electric quadrupole transition in $^{199}Hg^+$. The linewidth here is about 86 Hz; we believe this is the highest Q ever reported in atomic or molecular physics.

(3) Quantum Zeno effect.

Laser-cooled ions stored in Penning traps are nearly free from collisions and other perturbations that could cause relaxations. This, and the fact that their states can easily be manipulated with rf and laser radiation, makes them well suited for demonstrating certain aspects of quantum measurement theory. The quantum Zeno effect is the inhibition of transitions between states by frequent measurements (R. J. Cook, Phys. Scripta T21, 49 (1988)). We have observed this effect in the (m_I=3/2, m_J=1/2) $\leftrightarrow$ (1/2, 1/2) $^9Be^+$ ground-state rf transition. The measurements are short pulses of light tuned between the (3/2, 1/2) ground state and the $^2P_{3/2}$(3/2, 3/2) excited state. If the ion is found to be in the (3/2, 1/2) ground state, it scatters a few photons during the measurement; if it is in the other, it scatters no photons. In the latter case the wavefunction "collapse" is due to a null measurement. (M. Porrati and S. Putterman, Phys. Rev. A36, 929 (1987)) The dynamics of this system are essentially the same as those which are predicted to lead to nonexponential spontaneous decay at short times. However, observing the Zeno effect in spontaneous decay would be extremely difficult.

This experimental demonstration, although fairly simple, has led to rather widespread interest. Aside from our publication in Phys. Rev. A, several invited talks on the subject have been given and the subject has stimulated lively discussion. It has also been written about in Science, Science News, The New Scientist, Scientific American, Discover, and Nature. Most of the serious discussion from practicing scientists centers around the notion of wavefunction "collapse". As some scientists have pointed out, this concept is excess "baggage" and one only needs to talk about correlations between state preparation and detection. Nevertheless it seems like a useful idea in describing our experiment and is accepted by most.

(4) Synchrotron frequency divider.

A single electron in a magnetic field can have its cyclotron motion excited by an oscillating electric field. Usually, the excitation is made at a frequency which coincides with the cyclotron frequency of the electron, but excitation at a multiple of the cyclotron frequency is also possible. This parametric excitation of a single electron (whose orbit is well controlled) appears to be of fundamental interest because it is one of the simplest systems in which to study parametric excitation and because it should be possible to study parametric excitation in both the quantum mechanical and classical regimes in the same system.

A second feature of this system may be of great practical importance. For example, if the parametric excitation can be detected by observing the motion of the electron at its fundamental frequency, the resulting device acts as a frequency divider. That is, we inject a certain frequency into the device and measure a submultiple of the input frequency. For the electron, this parametric downconversion process can in principle be extended to very high orders; that is it should, in principle, be possible to inject a laser frequency and read out a microwave frequency (the cyclotron frequency). (see D. J. Wineland, J. Appl. Phys. 50, 2528 (1979) and Y. J. Ding and A. E. Kaplan J. Opt. Soc. Am. B6, 1299, (1989) and references therein). Such a device would be extremely useful as a meterological tool since as yet no devices exist which can compare in a phase coherent way laser frequencies with microwave frequencies. Such a device is a crucial component in the overall development of an optical frequency standard because for a frequency standard to generate time, one must be able to count the cycles of the radiation.

Because this project is, relatively speaking, in its infancy, we are now studying the first steps in the realization of the device - that is the division by two and three in the microwave region. Although not useful as a practical measuring device, these first experiments will allow us to study some of the basic physics of the parametric excitation such as electron orbit stability, required drive stability, and requirements of the associated apparatus.

In this last year the electron Penning trap apparatus has been made operational. In a first run, single electrons were stored and cooled by sideband excitation. Although this work has been previously demonstrated (most notably by the University of Washington groups of Dehmelt and Van Dyck) it is a significant first step in the study of the parametric excitation process and represents an important milestone. Additionally, the cyclotron motion of the electron has been excited parametrically at twice the cyclotron frequency; this is the first time this has been accomplished. After this first run, the apparatus is currently being modified to make minor improvements before trying higher order parametric excitation.

(5) Linear rf Trap and High Resolution Microwave Spectroscopy of Hg^+

The main advantage of using a single ion in a quadrupole rf (Paul) trap is that the kinetic energy of micromotion can be on the order of the secular motion energy. For a single $^{199}Hg^+$ ion cooled to the Doppler-cooling limit (as achieved in our experiments), the second-order Doppler shift would be $\langle\Delta\nu_{D2}/\nu_o\rangle = -2.3 \times 10^{-18}$. In a quadrupole ion trap, two or more ions in the trap are pushed from the center of the trap by the mutual Coulomb repulsion and the second-order Doppler shift is significantly higher. Consider the trap shown in Fig. 4. This design is essentially the same as that described by Prestage et al. (J. Appl. Phys. 66, 1013 (1989)) and Dehmelt (in Frequency Standards and Metrology, ed. by A. DeMarchi, (Springer-Verlag, Berlin, 1989). In the trap of Fig. 4, the rf electric fields are transverse to the trap axis for the entire z extent of the trap. If a single "string" of ions is trapped along the z axis, then the kinetic energy of micromotion is about equal to the kinetic energy in the secular motion. Therefore, the fractional second-order Doppler shift could be as low as $5kT/2mc^2$. This is 5/6 of the value for a single ion in a quadrupole rf trap because of the absence of rf micromotion along the z direction. At the Doppler-cooling limit, this gives $\Delta\nu_{D2}/\nu_o \simeq -2 \times 10^{-18}$ for all Hg^+ ions in the string.

Use of the trap of Fig. 4 would allow $N \gg 1$ giving good signal-to-noise ratio and still yield a small second-order Doppler shift. Assume 50 ions stored along the z axis like "beads on a string" with ion spacings of approximately 5 μm. With this spacing each ion could be independently detected by using an image detector (so far we have seen up to 8 individual ions along the z axis of a quadrupole trap). Therefore each ion could be treated as an independent atomic clock where the clock transition could be detected with 100% efficiency. For a Ramsey interrogation time of $T_R = 100$ s and $\omega_o/2\pi = 40.5$ GHz (the ground state hyperfine transition for $^{199}Hg^+$) the frequency stability of this clock "ensemble" would be $\sigma_y(\tau) = 5.5 \times 10^{-14}\tau^{-1/2}$. For these long interrogation times, sympathetic cooling might be required to avoid heating while the Hg^+ optical pumping laser was turned off to avoid light shifts during the Ramsey period. The ions used to cool the Hg^+ ions would also find a position in the string of ions along the z axis.

Such a linear trap would have two important applications for frequency standards: (1) It appears that a microwave frequency standard (described briefly in the last paragraph) would have excellent short term stability and an accuracy considerably better than 1 part in 10^{15}. (2) Such an array of ions could significantly improve the signal-to-noise ratio in the Hg^+ optical experiments thereby relaxing the requirements on laser "local oscillator" spectral purity (discussed in part (2) above).

With this in mind, we have just finished construction of the trap in Fig. 4 (rod spacings of approximately 1mm). Tests of the trap are just getting underway.

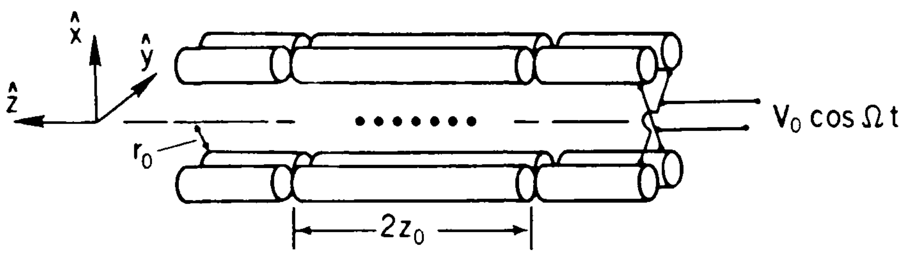

Fig. 4. Linear trap configuration. The alternating rf voltage $V_0\cos\Omega t$ is assumed to be applied to diagonally opposing electrodes as shown. We assume the end portions of the electrodes are long enough that the resulting rf potential at the position of the ions is independent of z, so that the rf electric fields are parallel to the x-y plane. To trap ions along z, we assume the center four electrodes are at static ground potential and the two sets of four electrodes on either end are at a static potential U_0 ($U_0 > 0$ to trap positive ions). The average position of the ions could be made to coincide with the rf electric field null by applying slightly different static potentials to the four central rods to correct for contact potential offsets etc. This geometry would allow laser beams to be directed along the z axis.

(6) Laser Cooled Refrigerator and Detector

A single trapped ion, laser-cooled into its quantum ground state of motion, may be used as a quantum-limited detector for RF signals applied to the trap endcaps. The ion can also function as a quantum-limited refrigerator; a signal source consisting of a high Q oscillator may be placed in its quantum ground state via coupling to the ion. Parametric drives may be used to cool and detect source modes other that the one directly coupled to the ion. Squeezed states of the source can also be generated. These principles should be applicable to the cooling and detection of the motion of a charged particle in a Penning trap; coupling to the ion is obtained by connecting the Penning trap and ion trap electrodes together.

We have theoretically analyzed such a "coupled trap" experiment, and show that the charged particle may be placed in its ground state and single quantum excitations of the motion and single spin flips detected. This technique may substantially improve the accuracy of measurements of the electron (or proton) magnetic moments, and electron-positron (or proton-antiproton) magnetic moment and mass ratios.

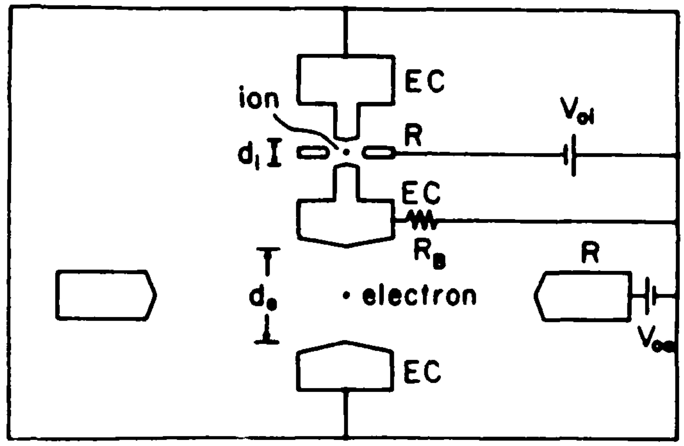

Fig. 5. Coupled trap experiment. EC: endcap electrode, R: ring electrode. The central endcap is common to the two traps and is connected to the shield by resistor R_B. The trap electrodes and shield (outer boundary) are drawn to scale, with d_e = 0.4 cm, and are assumed to have cylindrical symmetry.

As a first experiment along these lines, we have designed and are now constructing the coupled Penning trap which is shown schematically in Fig. 5. The smaller trap will contain Be^+ ions which are to be cooled to their ground state by stimulated Raman transitions (discussed in our paper). The larger trap will contain an electron which is the test ion. The spacing of the electrodes on the electron trap is 0.4 cm. A critical element is the coupling time constant between the ion and electron which we calculate to be 0.88 s for the trap shown when the axial frequencies adjusted to be 5 MHz. Axial frequencies must be held to better than 1Hz precision over this coupling time. To reduce spurious heating from thermal noise, the apparatus will be kept at liquid He temperature. Currently the trap is being fabricated; we hope to do initial tests by the end of this summer ('90).

(7) <u>Penning Trap Density Limitations</u>

We have studied a specific mechanism for practical density limitations of charged particles in a Penning trap. This affects not only our frequency standard experiments but all Penning trap experiments which try to achieve high density.

By changing the angular momentum of the ions using torque about the z axis from the laser beam, we have been able to achieve all permissible rotation frequencies of the cloud. The density n of the cloud and the rotation frequency ω are related by the expression $n = m\omega(\Omega-\omega)/2\pi q^2$ where m and q are the ion's mass and charge and Ω is the single particle cyclotron frequency. Therefore we are able to achieve the maximum density theoretically possible - the "Brillouin" density $m\Omega^2/8\pi q^2$. This however requires that we align the trap electric axis with the magnetic field axis to better than 0.01 degrees. In most Penning trap experiments, this degree of alignment is very hard to achieve. In that case, we find that the rotation frequency and therefore the density is limited by excitation of a quadrupole oscillation mode of the ion cloud by static electric field axial asymmetries. We have obtained good agreement between theory and experiment in these studies; this work is currently being written up. From a practical standpoint, this kind of mode excitation from field asymmetries will limit the ion densities in most Penning trap experiments. These results will therefore have implications for all experiments using Penning traps.

IV. PUBLICATIONS. ETC. SINCE LAST PROPOSAL

A. PAPERS PUBLISHED IN REFEREED JOURNALS

1. "Test of the Linearity of Quantum Mechanics by rf Spectroscopy of the $^9Be^+$ Ground State," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert and D. J. Wineland, Phys. Rev. Lett. 63, 1031(1989).

2. "Quantum Zeno Effect," W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, Phys. Rev. A41, 2295 (1990).

3. "Microplasmas," J. J. Bollinger and D. J. Wineland, Sci. Am., vol. 262, no. 1, Jan. 1990, p. 124.

3. "Quantum-Limited Cooling and Detection of Radio-frequency Oscillations by Laser Cooled Ions," D. J. Heinzen and D. J. Wineland, Phys. Rev. A42, 2977 (1990).

B. PAPERS SUBMITTED TO REFEREED JOURNALS (not yet published)

1. "Rotational Equilibrium and Low Order Modes of a Nonneutral Ion Plasma," D. J. Heinzen, J. J. Bollinger, F. L. Moore, W. M. Itano, and D. J. Wineland, submitted.

2. "Progress at NIST towards Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, and M. G. Raizen, IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control; accepted for publication.

3. "Comment on "Nonlinear Magneto-Optics of Vacuum: Second Harmonic Generation"", M. G. Raizen and Baruch Rosenstein, submitted.

4. "A 303-MHz Frequency Standard Based on Trapped Be^+ Ions," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control; submitted.

C. BOOKS (and sections thereof) PUBLISHED

1. "The Digitized Atom and Optical Pumping," D.J. Wineland, W.M. Itano, J.C. Bergquist and R.G. Hulet, in Atomic Physics 11, ed. by S. Haroche, J.C. Gay, G. Grynberg, (World Scientific Press, Singapore, 1989) p. 741.

2. "Liquid and Solid Phases of Laser Cooled Ions," S.L. Gilbert, J.C. Bergquist, J.J. Bollinger, W. M. Itano, and D.J. Wineland, in Atomic Physics 11, ed. by S. Haroche, J. C. Gay, and G. Grynberg (World Scientific Press, Singapore, 1989) p. 261.

3. "Progress at NIST Towards Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, and C. S. Weimer, proc. 43rd Annual Symposium on Frequency Control, Denver, June, 1989, IEEE Catalog No. 89CH2690-6.

4. "Observation of Correlations in Finite, Strongly Coupled Ion Plasmas," J. J. Bollinger, S. L. Gilbert, D. J. Heinzen, W. M. Itano, and D. J. Wineland, in Strongly Coupled Plasma Physics, ed. by S. Ichimaru, (Elsevier Science Publishers B.V. / Yamada Science Foundation, 1990) p. 177.

5. "Hg^+ Single Ion Spectroscopy," J. C. Bergquist, F. Diedrich, W. M. Itano, and D. J. Wineland, in Laser Spectroscopy IX, ed. by M. S. Feld, J. E. Thomas, and A. Mooradian (Academic, San Diego, 1989), p. 274.

6. "Laser Cooling and the Formation of Coulomb Crystals," J. C. Bergquist, 1991 Yearbook of Science and Technology, McGraw Hill Publishing Co.

7. "Liquid and Solid Plasmas," J. J. Bollinger, S. L. Gilbert, D. J. Heinzen, W. M. Itano, and D. J. Wineland, in Atomic Processes in Plasmas, ed. by Y. K. Kim and R. C. Elton, AIP Conference Proceedings 206, (American Institute of Physics, New York, 1990) p. 152.

D. BOOKS (and sections thereof) SUBMITTED

1. "Quantum Optics of Single, Trapped Ions," W. M. Itano, J. C. Bergquist, F. Diedrich, and D. J. Wineland, proc. Sixth Rochester Conference on Coherence and Quantum Optics, Rochester, N. Y., June, 1989, to be published.

2. Test of the Linearity of Quantum Mechanics by RF Spectroscopy of the $^9Be^+$ ground State," D. J. Heinzen, J. J. Bollinger, W. M. Itano, S. L. Gilbert, and D. J. Wineland, ibid.

3. "Cooling Methods in Ion Traps," W. M. Itano, J. C. Bergquist, J. J. Bollinger, and D. J. Wineland, chapter in Physics with Charged Particles in a Trap, edited by G. Gabrielse and G. Werth, submitted.

4. "Trapped Atoms and Laser Cooling," D. J. Wineland, "essay" for undergraduate text Physics, by Paul Tipler, submitted.

5. "Progress at NIST on Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, M. G. Raizen, and C. S. Weimer, proc. 4th European Frequency and Time Forum, Neuchatel, March 1990, to be published.

6. "Atomic Physics Tests of Nonlinear Quantum Mechanics," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, in Atomic Physics 12, proc. 12th Int. Conf. on Atomic Physics, ed. by R. Lewis and J. Zorn, A. I. P. Conference proceedings, to be published.

E. INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. Seventh APS Topical Conference on Atomic Processes in Plasmas, Gaithersburg, Md., October, 1989, D. J. Wineland.
2. Optical Society of America, Annual Meeting, Orlando, Fla., October, 1989, W. M. Itano.
3. Winter College on High Resolution Spectroscopy, International Centre for Theoretical Physics, Trieste, Italy, January, 1990, W. M. Itano.
4. European Forum on Time and Frequency, Neuchatel, Switzerland, March, 1990, D. J. Wineland.
5. Precise Frequency Measurements Meeting, Communications Research Laboratory, Tokyo, Japan, March 1990, W. M. Itano.
6. Ninth International Laser Spectroscopy Conference, Bretton Woods, New Hampshire, June, 1989, J. C. Bergquist.
7. Gordon Conference on Atomic Physics, Wolfboro, New Hampshire, July, 1989, J. C. Bergquist.
8. Spring Meeting of APS, Washington, D. C., April, 1990, D. J. Wineland.
9. Meeting on "Light Induced Kinetic Effects on Atoms, Ions and Molecules," Pisa, Italy, May, 1990, J. C. Bergquist.
10. APS Division on Atomic, Molecular, and Optical Physics (DAMOP), Annual Meeting, Monterey, Ca., May, 1990, J. C. Bergquist and D. J. Wineland.
11. Workshop on the foundations of Quantum Mechanics, Santa Fe, N. M., May 1990, D. J. Heinzen.
12. Conference on Precision Electromagnetic Measurements, Ottawa, Canada, June, 1990, W. M. Itano.
13. International Conference on Atomic Physics (ICAP), Ann Arbor, Michigan, July, 1990, J. J. Bollinger.
14. Gordon Conference on Few Body Systems, Proctor Academy, N. H., Aug. 1990, D. J. Wineland.
15. U. S./ Japan Seminar on "Quantum Electronic Manipulation of Atoms and Fields," Kyoto, September, 1990, D. J. Wineland.

F. OTHER INVITED TALKS (Colloquia etc.)

1. Univ. of Notre Dame, Notre Dame, Ind. September, 1989, J. J. Bollinger.
2. Laval University, Quebec, Canada, October, 1989, D. J. Wineland.
3. Rochester Univ., Rochester, N. Y., November, 1989, D. J. Heinzen.
4. Univ. of Oregon, Eugene, Oregon, November, 1989, D. J. Wineland.
5. Cal Tech, Pasadena, Ca., November, 1989, D. J. Wineland.
6. Washington Univ., St. Louis, Mo., December, 1989, W. M. Itano.
7. National Physical Laboratory, Teddington, England, December, 1989, D. J. Wineland.
8. Univ. of Wisconsin, Madison, Wisconsin, January, 1990, D. J. Heinzen.
9. M I T, Cambridge, Mass., February, 1990, D. J. Heinzen.
10. Lawrence Berkeley Laboratory, Berkeley, Ca., February, 1990, W. M. Itano.
11. Stanford Linear Accelerator, Stanford, Ca., February, 1990, W. M. Itano.
12. Univ. of Calif., San Diego, La Jolla, Ca., February, 1990, D. J. Wineland.
13. Ecole Normale, Paris, France, March, 1990, D. J. Wineland.

14. General Electric, Schnectady, N. Y., March, 1990, J. J. Bollinger.
15. Tokyo Institute of Technology, Yokohama Japan, April, 1990, W. M. Itano.
16. Okayama Univ., Okayama, Japan, April, 1990, W. M. Itano.
17. University of Electrocommunications, Tokyo, Japan, April, 1990, W. M. Itano.
18. Univ. of Tokyo, Tokyo, Japan, April, 1990, W. M. Itano.
19. Univ. of Chicago, Chicago, Ill., April, 1990, J. J. Bollinger.
20. IBM Almaden Research Center, San Jose, Ca., May, 1990, D. J. Wineland.
21. Rice University, Houston, Texas, January, 1990, J. J. Bollinger.
22. UCLA, Los Angeles, January, 1990, D. J. Heinzen.
23. Univ. of Washington, Seattle, September, 1990, D. J. Heinzen.
24. George Washington Univ. / NSF Colloquium, September, 1990, D. J. Wineland.

G. HONORS/AWARDS/PRIZES

1. Election to Fellow of the American Physical Society, J. C. Bergquist.
2. 1989 Samuel Wesley Stratton Award (NIST), for ion frequency standard development. Shared by J. C. Bergquist, J. J. Bollinger, W. M. Itano, and D. J. Wineland.
3. 1990 Davisson-Germer Prize (APS), D. J. Wineland.